VARIABLE OPTICAL ATTENUATOR ON AN ELECTRO-OPTICAL LAYER

FIELD OF THE INVENTION

[0001] The present invention relates generally to optical communications device technology, and more particularly, to variable optical attenuators formed on electro-optical materials.

BACKGROUND OF THE INVENTION

[0002] High-speed optical networks transmit information long distances as light signals through optical fibers. Amplification of optical signals is required at regular intervals along the network to maintain signal strength, preferably using optical amplifiers. Since some advanced networking techniques transmit many channels simultaneously through the same fiber, it is important that the gain is the same for each channel. For example, networks that use wavelength division multiplexing (WDM) transmit many channels over the same fiber, with each channel at a different wavelength. Since current optical amplifiers have wavelength dependent gains, repeated amplification can distort the information being transmitted. Wavelength-dependent gain can be overcome by optical equalization of the different signal channels. In practice, this equalization is performed by use of a variable optical attenuator (VOA).

[0003] There are several types of VOAs currently available. In one type of VOA, a Mach-Zehnder interferometer has a material in the optical path having a temperature dependent refractive index (the "thermo-optic effect"). The interferometer is configured such that a change in the temperature of the thermo-optic material results in a change in the output light intensity. Attenuation is thus adjusted by control of the temperature of the thermo-optic material. Although thermo-optic VOAs have good optical coupling properties and are polarization independent, they suffer from high power usage and a slow response time of greater than 10 ms, and thus they are not appropriate for high speed networking.

[0004] Another currently available VOA employs microelectromechanical system (MEMS) elements, in which movable, micro-elements are used to attenuate light. MEMS devices are also rather slow, with response times on the order of milliseconds, and have reliability issues resulting from the many moving parts of the VOA.

[0005] In addition to speed and reliability, there is also a need to have VOAs that can be assembled into arrays or into other devices. For the large number of channels envisioned for

WDM networks, it would be a great advantage to be able to fabricate VOAs of smaller size, to assemble VOAs into arrays, and to incorporate them into other WDM devices, such as multiplexers or demultiplexers. Heretofore, it has been difficult to configure prior art VOAs into arrays or within other devices.

[0006] Therefore, it would be desirable to have a VOA that is faster than currently available devices, and that can be assembled in large numbers as an array. It is also desirable to have a VOA that is manufactured by techniques that allow for integration into other WDM devices.

SUMMARY OF THE INVENTION

[0007] The present invention solves the above-identified problems with VOAs by providing waveguides having attenuation that is controlled by application of an electric field to an electro-optical material that is part of the waveguide or is adjacent to a cladding of the waveguide.

[0008] It is one aspect of the present invention to provide a variable optical attenuator that uses the electro-optic effect to controllably change the transmission of light through a waveguide. In one embodiment of the invention, the waveguide is adjacent to an electro-optical material having a refractive index that can be varied between a first refractive index and a second refractive index by application of a voltage difference to electrodes adjacent to the electro-optical material. When the electro-optical material has a refractive index equal to the first refractive index, the waveguide is a low-loss waveguide. When the electro-optical material has a refractive index equal to the second refractive index, light is coupled from the waveguide into the electro-optic material. By including a plurality of such waveguides between a demultiplexer and a multiplexer, a WDM signal can be separated into individual channels, the individual channel intensities can be varied, and an attenuated WDM signal can be reconstituted.

[0009] In another aspect of the present invention, polarization independent variable optical attenuators are provided using electro-optical materials. In one embodiment, a waveguide is provided having a first waveguide and second waveguide separated by a polarization rotating element that rotates the light passing between the two waveguides by 90 degrees. The electro-optical material attenuates light by preferentially allowing leakage from the waveguide according to the polarization of light therein. Rotating the polarization between two waveguides provides polarization independent attenuation. In an alternative embodiment, a waveguide is provided as

a first waveguide that includes a first electro-optical material and a second waveguide that includes a second electro-optical material. The first and second electro-optical materials differ in that in the first material the ordinary refractive index is greater than the extraordinary refractive index, and in the second material the ordinary refractive index is less than the extraordinary refractive index.

[0010] In another aspect of the present invention, an attenuator is provided having a waveguide with a core of a first refractive index, a cladding of a second refractive index, and an electro-optical material of a third refractive index. The value of the third refractive index varies according to the electric field from the first refractive index to the second refractive index.

[0011] In one aspect of the present invention, a device is provided for variably attenuating an optical signal. The device includes a waveguide having a cladding and an electro-optical material adjacent to at least a portion of the cladding. At least two electrodes are also included to produce an electric field within the electro-optical material, and the attenuation of light through the waveguide varies with an applied voltage difference to the electrodes. In one embodiment of the present invention, the electro-optical material is a substrate on which the device is formed. In an alternative embodiment, the electro-optical material is a layer formed on a silicon substrate.

[0012] In another aspect of the present invention, a device is provided for variably attenuating a plurality of optical signals. The device includes a plurality of waveguides to each attenuate one of the plurality of optical signals. Each of the plurality of waveguides has a cladding and an electro-optical material layer adjacent to at least a portion of the cladding. The device also includes at least two electrodes associated with each of the plurality of waveguides. The electrodes produce an electric field within an associated electro-optical material layer. The attenuation of individual ones of the plurality of optical signals varies with an applied voltage difference to the associated electrodes. In one embodiment of the present invention, the device further includes a silicon substrate to support the electro-optical material. In an alternative embodiment, the substrate is an electro-optical material.

[0013] In another aspect of the present invention, a device for variably attenuating a plurality of optical signals each between an input and an output. The device includes a plurality of waveguides, one for each optical signal. Each waveguide includes a core between an input and

an output having a first refractive index, a cladding surrounding a substantial length of the core and having a second refractive index different from the first refractive index, an electro-optical material surrounding at least a portion of the cladding, and at least two electrodes to produce an electric field within the electro-optical material. The attenuation of each of the plurality of optical signals is individually varied by an applied voltage difference to corresponding ones of the at least two electrodes. In one embodiment of the present invention, the electro-optical material has a third refractive index variable by the electric field between the value of the first refractive index to the value of the second refractive index.

[0014] In a further aspect of the present invention, an array of variable optical attenuators is provided that is more reliable and less expensive than those of the prior art.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] The foregoing aspects and the attendant advantages of this invention will become more readily apparent by reference to the following detailed description when taken in conjunction with the accompanying drawings wherein:

[0016] FIG. 1 is a schematic of an array of VOAs of the present invention for gain control in a WDM network;

[0017] FIG. 2A is a perspective view of a section of a first embodiment VOA of the present invention as a VOA formed on an electro-optic film;

[0018] FIG. 2B is a section view 2B-2B of FIG. 2A;

[0019] FIG. 3 is a top view of an array of two VOAs of FIG. 2;

[0020] FIG. 4 is a sectional side view 4-4 of FIG. 3 also illustrating the propagation of light through the VOA;

[0021] FIGS. 5A-5E are schematic diagrams showing the formation of the first embodiment VOA at several sequential steps in a first embodiment manufacturing process;

[0022] FIG. 6 is a perspective view of a second embodiment VOA of the present invention as a VOA formed on an electro-optic substrate;

[0023] FIG. 7 is a sectional side view through one second embodiment VOA of the present invention, illustrating the propagation of light through the VOA;

[0024] FIG. 8A is a top view and FIG. 8B is a sectional side view illustrating an third embodiment VOA for providing polarization independent attenuation;

[0025] FIG. 9 is a side sectional view illustrating a fourth embodiment VOA for providing polarization independent attenuation; and

[0026] FIG. 10 is a graph showing the results of calculations that predict the effect of lower cladding thickness on the attenuation through the inventive VOA.

[0027] Reference symbols are used in the Figures to indicate certain components, aspects or features shown therein, with reference symbols common to more than one Figure indicating like components, aspects or features shown therein.

DETAILED DESCRIPTION OF THE INVENTION

[0028] The present invention is directed to a VOA that overcomes the problems associated with currently available VOAs. For example, VOAs provided in accordance with the present invention are faster than current VOAs, and can be manufactured in closely packed arrays. They are thus readily usable in WDM networks. Also, the inventive VOAs are manufactured using conventional fabrication processes, thereby allowing them to be integrated into other networking devices.

[0029] FIG. 1 shows a schematic of a VOA array **100** of the present invention as used in a gain equalizer **10** of a WDM network. A source **11** of a WDM signal **17'** is shown being transmitted through a fiber **13** to gain equalizer **10**. As described below, gain equalizer **10** separately adjusts the intensity of each WDM signal **17'** to produce an equalized signal **21'** that is then transmitted through a fiber **25** to a WDM signal receiver **27**.

[0030] Signals **17'** and **21'** each contain 2 or more individual signals or channels. The number of channels is indicated herein as "n," where n is a number equal to or greater than 2. Individual ones of signal **17'** are denoted, in general, as signal **17**, as one of signals **17(1)**, **17(2)**, ... , **17(n)**, or in reference to one of signal **17(m)**, where m is a generalized index. Individual ones of signal

21' are denoted by a similar reference to signal **21**, one of signals **21(1)**, **21(2)**, ... , **21(n)**, or by reference to index m, as in signal **21(m)**.

[0031] As shown in FIG. 1, gain equalizer **10** further includes a demultiplexer (DMUX) **15**, an array intensity monitors **18**, and a multiplexer (MUX) **23**. VOA array **100** and intensity monitor array **18** each include n separate components to attenuate and monitor each of the n channels. Thus VOA array **100** includes n separate VOAs, specifically VOA **101(1)**, VOA **101(2)**, ... , VOA **101(n)**. Individual ones of the array of VOAs are referred to herein as VOA **101**, or by a number other than n, for example the m^{th} VOA is referred to as VOA **101(m)**. Intensity monitor array **18** includes n separate intensity monitors, specifically intensity monitors **19(1)**, **19(2)**, ... , **19(n)**, or in general, intensity monitor **19**. Each of the n channels of the WDM signal is processed by one VOA and is monitored with one intensity monitor.

[0032] Also included in gain equalizer **10** is a controller **29** to adjust the attenuation of each VOA **101**. Specifically, each intensity monitor **19** monitors the light signal passing through the monitor and provides a signal **28** to controller **29** that is proportional to the intensity of the signal **17**. In one embodiment, controller **29** then generates an electrical signal **30** according to signal **28** and the programming of the controller that acts to modify the attenuation of individual ones of VOA **101**. In another embodiment, gain is controlled by constantly monitoring a small portion of signal **28**.

[0033] DMUX **15** accepts a WDM signal **17'** and separates the WDM signal into **n** separate signals, **17(1)**, **17(2)**, ..., **17(n)**. Each of the **n** signals proceeds through a corresponding one of the individual VOA **101**, through one of the **n** intensity monitors **19**, and into MUX **23** that recombines the **n** signals into equalized WDM signal **21'**.

[0034] A first embodiment VOA of the present invention is shown in more detail in FIGS. 2-4, where FIG. 2A is a perspective view of a section of VOA **101** formed on a layer **209** of an electro-optical material, FIG. 2B is a section view 2B-2B of FIG. 2A, FIG. 3 is a top view of an array of two VOAs of FIG. 2, indicated as VOA **101(m)** and **101(m+1)**, and FIG. 4 is a sectional side view 4-4 of FIG. 3 also illustrating the propagation of light through the VOA. As shown in FIGS. 3 and 4, each VOA **101** extends from an input **301** to an output **303**. The sectional views of FIGS. 2A and 2B further show the VOA **101** structure between input **301** and output **303** to

include a waveguide core **201** surrounded by a cladding **203**, a pair of electrodes **213**, layer **209** of an electro-optical material, and a substrate **211** that supports layer **209**. Input **301** and output **303** correspond to the ends of core **201**, where light is coupled into the core at the input by a fiber **40 1** and where is coupled out of the core at the output into a fiber **403**.

[0035] The materials of core **201** and cladding **203** are optically transparent materials for wavelengths of the WDM signal. The materials of layer **209** and substrate **211** can be, but are not required to be, optically transparent at the WDM wavelengths. The material optical properties and dimensions, as well as the spacing and placement of electrodes **213**, are selected to controllably pass, attenuate, or block light traveling across VOA **101** from input **301** and towards output **303** according to the electro-optically controllable refractive index of layer **209**, as follows. When layer **209** has a refractive index equal to the refractive index of core **201**, the dimensions and materials of VOA **101** are such that the core and cladding **203** are a high-loss waveguide between input **301** and output **303**. When layer **209** has a refractive index equal to that of lower cladding **207**, the dimensions and materials of VOA **101** are such that core **201** and cladding **203** are a low-loss waveguide of light entering core **201**. At refractive index values between that of core **201** and lower cladding **207**, a controllable fraction of the light is transmitted across the variable optical attenuator **101**.

[0036] Core **201** is preferred to have a cross-sectional shape that is rectangular or square. As shown in the preferred embodiment of FIG. 2B, core **201** has a square cross-section with each side having a length **X**. The top and side cladding layers **205b** and **205a** each have a thickness **Y**. The lower cladding **207** has a thickness **T**. Layer **209** has a thickness **W**, and substrate **211** has a thickness **Z**. In an alternative embodiment, not shown, core **201** has a cross-section that is not square and is, for example, rectangular.

[0037] Core **201** and cladding **203** cooperate according to their dimensions and optical properties, specifically having different refractive indices, to act as a waveguide for light between input **301** and output **303**. In a preferred embodiment, cladding **203** includes an upper cladding **205** and a lower cladding **207** as shown in FIGS. 2 and 4. Upper cladding **205** can further be differentiated by the portions shown in FIG. 2B as side claddings **205a** and an upper cladding **205b**. Preferably the upper cladding **205** and lower cladding **207** have the same

refractive index.

[0038] It is preferred that attenuation of light through core **201** is modified by changing the refractive index of material adjacent lower cladding **207** according to the voltage difference applied to the pair of electrodes **213**, and that little or no voltage difference is required for VOA **101** to be a low-loss waveguide. When no voltage difference is applied, the refractive index of layer **209** is the same as that of lower cladding **207**, and VOA **101** is a low-loss waveguide. The pair of electrodes **213** is positioned relative to layer **209** such that, when a voltage difference is applied to the electrodes, an electric field is established that affects the refractive index of layer **209** in a region **215** adjacent to cladding **203**. For a thin layer **209**, for example when the thickness is 10 μm or less, a sufficiently large voltage applied to electrodes **213** modifies the refractive index of the whole film thickness W. In general, electrodes **213** and layer **209** are positioned relative to cladding **203**, core **201**, and substrate **211** such that electrodes supplied with a potential difference result in a uniform change in refractive index of the layer from input **301** to output **303**. It is preferred that electrodes **213** extend along VOA **101** from input **301** to output **303** and that they are transversely spaced on either side of core **201**. The fraction of light entering input **301** that emerges from output **303** can be controlled according to the voltage difference applied to each pair of electrodes **213**. The control of the light signal through VOA **101** is thus achieved by modifying the refractive index of electro-optic layer **209** by the application of an electric field to the layer according to the voltage difference across electrodes **213**.

[0039] The electro-optic effect is intrinsically very fast, resulting from atomic level changes to the electro-optical material. These changes can occur with speeds faster than several nanoseconds. The operational speed of VOA **101** can be as fast as from about 1 to about 500 nanoseconds. One limiting speed factor is delays in the electronics driving the VOA due to wiring and propagation of the electrical signal from electrodes.

[0040] The refractive index of layer **209** is variable according to the electro-optic effect to change between the refractive index of the core and the refractive index of the cladding. Preferred materials for core **201** include optical polymers, including but not limited to low loss optical polyimides and epoxies. Preferred materials for cladding **203** are the same as for core

201 with dopants added to modify the cladding refractive index to be slightly smaller than that of the core, for example 0.2% to 1%. Preferred materials for substrate **211** include, but are not limited to materials typically used in manufacturing of substrate wafers, such as silicon.. Preferred materials for layer **209** include materials that have refractive index ranges between those of the core and cladding and have electro-optic coefficients that allow their use with reasonable applied voltages.

[0041] In one embodiment, core **201** and cladding **203** are formed from one type of optical polymer, and layer **209** is formed from the same or a similar polymer with additives, including but not limited to electro-optic polyimides, that make the polymer electro-optic.

[0042] In another embodiment, core **201** and cladding **203** are fabricated from thin films of higher refractive index materials then layer **209**, which is formed material which include, but are not limited to: $LiNbO_3$, $LiTaO_3$, KDP, KTP, and $LiIO_3$. The operation of VOA **101** with these materials requires an electric field on the order of about 1 to about 100 V/μm for appropriate modification of the refractive index. Preferred electrode spacing to produce his electric field are from about 5 to about 20 μm, with a preferred voltage difference of about 10 to about 100 volts.

[0043] The application of a voltage difference to the pair of electrodes **213** modifies the refractive index of layer **209** near lower cladding **207** to the value away from that of the cladding and towards the refractive index of core **201**. Under these conditions a fraction of the light propagating through core **201** is coupled out of the waveguide according to the value of the refractive index and the thickness **T** of cladding between the core and layer **209**. FIG. 4 is a sectional side view 4-4 of FIG. 3 illustrating the propagation of light through the VOA **101**. Light from input **301** is shown schematically at arrow **A** entering core **201** from fiber **401**. When the refractive index of layer **209** is the same as that of cladding **203**, and specifically of lower cladding **207**, the majority of light propagating in core **201** travels from the input **301** to the output **303**, and into fiber **403**, as indicated schematically as the output of light by arrow **E**. When the refractive index of layer **209** is the same as that of core **201**, light "leaks" from core **201** through lower cladding **207**, as indicated schematically by arrows **B**, **C**, and **D**. As indicated by arrows **B** and **C**, under these conditions light first propagates through lower cladding **207** and into that portion of layer **209** having the electro-optically elevated refractive index. When the

refractive index of substrate **211** is higher than that of layer **209**, cladding **203**, or core **201**, and as shown by arrow **D** light thus propagates into the substrate and away from the core. When the light arrives at output **303**, there is reduced light intensity at the output to be coupled out of core **201** and into fiber **403** because a proportion of the light has been redirected out of the core. In an alternative embodiment, layer **209** has a high absorption coefficient at the light wavelength, resulting in a higher loss.

[0044] As is also shown in FIG. 4, fiber **403** provides light to intensity monitor **19**, which provides electrical signal **28** to controller **29**. Controller **29** also provides voltage or voltages to electrodes **213**, thereby controlling the amount of attenuation of VOA **101**. Controller **29** can supply different voltages to different ones of VOAs **101** to control the gain of individual WDM signal channels.

[0045] One embodiment for light having a wavelength in the vicinity of 1550 μm has a refractive index of core **201**, R.I.(core), of 1.567, and a refractive index of cladding **203**, R.I.(cladding), of 1.563. Preferably, dimension **X** is 7 μm, thickness **Y** is from 5 μm to 30 μm, preferably 10 μm, thickness **T** is from zero to 10 μm, preferably from 3 μm to 5 μm, thickness **W** is from 3 μm to 10 μm of an electro-optical material, and substrate **211** has a refractive index that is greater than 1.57 with a dimension **Z** that can be greater than several millimeters. It is preferred that the thickness of layer **209** be optimized so that the electro-optically affected area is uniform in the region closest to core **201**. Layer **209** has a refractive index that can be varied from a value of R.I.(cladding) = 1.563 to a value of R.I.(core) = 1.567 according to the electric field within the electro-optical material as induced by the voltage difference between the pair of electrodes **203**. Thus the refractive index of layer **209** can be varied between the values of the refractive index of core **201** (R.I.(core)) and the refractive index of the cladding **203** (R.I.(cladding)). As noted above, it is preferred that when there is no voltage applied to electrodes **213**, that is in the absence of an electric field, that the refractive index of layer **209** is equal to the refractive index of cladding **203** (R.I.(cladding)). Under this condition, core **201** is surrounded by a lower index cladding **203** and layer **209**, and VOA **101** is a low-loss waveguide.

[0046] The attenuation of light through VOA **101** is illustrated in FIG. 10, which shows a graph of the results of calculations that predict the effect of the thickness of lower cladding on the

attenuation through the inventive VOA of FIG. 2-4. Upper cladding **205b** and side cladding **205a** have a thickness **Y** = 14 μm, and layer **209** is idealized as a "semi-infinite" material having a refractive index that is uniformly modified by the electro-optical effect. Calculations were performed to show the loss rate in dB/cm along VOA **101** as a function of the refractive index of layer **209** and the thickness **T**. While there is a wide range of losses as a function of refractive index, the largest variation occurs over a relatively small range of refractive index. Specifically, the loss rate has a minimum value when the refractive index of layer **209** equals the refractive index of lower cladding **207**, and has a maximum rate when the refractive index of layer **209** equals the refractive index of core **201**. In practice, this change in refractive index could occur for a voltage difference of about 50 to 100 volts applied over an electrode gap of about 5 μm to about 10 μm.

[0047] One of the main parameters in the optical design of VOA **101** is the thickness **T** of cladding **209**. One effect of the choice of the thickness **T** is a variation of VOA insertion losses. In general, the minimum loss rate is independent of thickness **T**, while the maximum loss rate increases for thinner thickness **T**. Thus the use of a small **T** can allow for a high output-to-input ratio ("extinction ratio") across VOA **101**. In one embodiment, VOA **101** has an extinction ratio of about 30-40 dB. In an alternative embodiment, the extinction ration is greater than 10 dB.

[0048] Another effect of the thickness **T** is the attenuation across the VOA. Smaller values of **T** result in greater attenuation. On the other hand, electro-optical materials usually have higher optical losses than do conventional waveguide materials. Thus, the closer core layer **201** is to layer **209**, the higher the insertion losses of the device. A preferred thickness **T** is from about 2 μm to about 5 μm.

[0049] There are several method for manufacturing the VOA of the present invention. FIGS. 5A-5E presents a first embodiment of a method for manufacturing VOA array **100** using techniques that are well known in the field of microelectronics and fiber optic manufacturing. FIG. 5A shows the manufacturing after several layers have been deposited on substrate **211**. The manufacturing begins with a substrate **211** which can be a silicon or other suitable material. Layer **209** of an electro-optical material having appropriate optical properties is deposited on substrate **211**. Layer **209** can be an electro-optic oxide, polymer or other material that is

deposited on substrate using spin-coating, spray-coating, sputtering, physical or chemical vapor deposition, or any other appropriate method. Next a metal layer **501** is deposited on layer **209** using sputtering, evaporation, or electro-plating methods, for example. A photoresist layer **503** is then coated and patterned through a photomask by means of lithography techniques well known in the industry. As shown in FIG. 5B, metal layer **501** not covered by photoresist **503** is removed by appropriate etching techniques, to form electrodes **213**.

[0050] The steps leading up to FIG. 5C shows the depositing of the lower cladding **207** and core **201**. First, lower cladding **207** is deposited. Lower cladding **207** can be an optical polymer or any other material useful as a cladding of a waveguide. Core **201** is then deposited on lower cladding **207**. As shown in FIG. 5D, the structure is then coated with another optical cladding material **505**. Lastly, the portions of material **505** and lower cladding **207** not surrounding core **201** are etched, resulting in an array of VOAs. The unremoved portions of material **505** are upper cladding **205** of VOA **101**.

[0051] An alternative embodiment VOA is shown as VOA **601** of FIG. 6. VOA **601** and **101** both have a core **201** surrounded by a cladding **203** and adjacent electrodes **213**. While VOA **101** has an electro-optic layer **209** and non-electro-optic substrate **211**, VOA **601** has a substrate **603** formed from an electro-optic material. Substrate **603** is preferably a substrate formed from the materials used to form layer **209**. Thus substrate **603** has a refractive index that is equal to that of cladding **203** when no electric field is applied, while that portion of substrate **603** that is in the presence of an electric field has a refractive index that approaches or is equal to that of core **201**. Thus the attenuation of VOA **601** is similar to that of VOA **101**, with the loss being affected by the refractive index of substrate **601** adjacent to cladding **203** and the thickness **T** of lower cladding **207**.

[0052] The manufacturing of VOA **601** is similar, though simpler, than that of VOA **101**. Specifically, in the manufacturing of VOA **601** there is no need to first deposit an electro-optic layer on a substrate, as substrate **603** is electro-optic. The remainder of the manufacturing steps are the same as for VOA **101**.

[0053] FIG. 7 is a sectional side view through VOA **601**, illustrating the propagation of light through the VOA. Light from input **301** is shown schematically at arrow **A** entering core **201**.

Since electrodes on at the interface between substrate **603** and lower cladding **207**, only a portion of substrate **603** will have a refractive index that changes with the voltage difference applied to electrodes **213**. Specifically, the portion of substrate **603** that is closest to lower cladding **207** is indicated as portion **605**. Portion **605** is not a well defined physical layer, as is layer **209**, but is a surface portion of substrate **603** whose refractive index changes due to the applied voltage difference at electrodes **213**.

[0054] When no voltage difference is applied to electrodes **213**, portion **605** has a refractive index that is the same as that of cladding **203**, and specifically of lower cladding **207**. The majority of light propagating in core **201** travels from the input **301** to the output **303**, as indicated schematically as the output of light by arrow **D**. When the refractive index of portion **605** is the same as that of core **201**, light "leaks" from core **201** through lower cladding **207**, as indicated schematically by arrows **B**, and **C**. As indicated by arrows **B** and **C**, under these conditions light first propagates through lower cladding **207** and into portion **605**. Since the refractive index of substrate **601** away from portion **603** is lower than that of portion **603**, light will continue propagating though portion **603**. When the light arrives at output **303**, there is little light remaining at the output of core **201**.

[0055] In general, electro-optical materials are birefringent, having polarization dependent refractive indices. In addition, the electro-optic coefficient (the change in refractive index with electric field) is also polarization dependent. For the VOAs of the present invention, attenuation can thus depend on the polarization of light traveling through the VOA. For example, light having a polarization mode that parallel to the cladding-electro-optical material interface may couple into the substrate, while light that has a polarization mode orthogonal to the interface may not couple into the substrate. Since light entering the VOA is likely to be unpolarized, the structure of VOA **101** or **601** may be modified to provide a polarization independent VOA that uses an electro-optical material adjacent to a waveguide cladding to attenuate light.

[0056] Several alternative VOA embodiments provide for polarization independent variable optical attenuation. A third embodiment VOA having polarization independent attenuation is shown in FIG. 8A as a top view and FIG. 8B as a sectional side view of VOA **800**. VOA **800** includes a first VOA section **801**, a second VOA section **803**, a TE/TM or TM/TE converter **805**

inserted within a slot in core **201**, and an index matching fluid between converter **805** and VOA sections **801** and **803**. Converter **805** is a device that can rotate the polarization of light by 90 degrees, such as a half-wave plate. Sections **801** and **803** are formed on a substrate **603** and are thus similar to VOA **601**. Alternatively, sections **801** and **803** can be formed on an electro-optic layer on top of a non-electro-optic substrate, and thus be similar to VOA **101**. In either case, electrodes **213** extend the length of VOA **800**.

[0057] As noted previously, light that is attenuated through VOA **101** or **601** as a result of the electro-optic layer transmitting polarized light. Thus the light remaining in core **201** and cladding **203** becomes polarized. Thus for example, unpolarized light entering input **301** that is attenuated is linearly polarized as it passes through VOA section **801**. TE/TM or TM/TE converter **805** rotates the polarization of the light remaining in core **201** and cladding **203** by 90 degrees. The remaining light is then attenuated as it traverses VOA section **803**.

[0058] A fourth embodiment VOA having polarization independent attenuation is shown in FIG. 9 as a side sectional view of VOA **900**. VOA **900** includes a first VOA section **901**, and a second VOA section **903** joined by an index matching epoxy **905**. Each VOA section **901** and **903** includes a core **201** and a cladding **203** Cladding **203** is attached to a first electro-optic substrate **907** (or electro-optic layer) to form first VOA section **901** and is attached to a second electro-optic substrate **909** (or elector-optic layer) to form second VOA section **903**. Substrate **907** has an ordinary refractive index that is greater than its extraordinary refractive index. Substrate **909** has an ordinary refractive index that is less than its extraordinary refractive index.

[0059] Light attenuated through VOA section **901** is polarized in the extraordinary mode, since core **201** is coupled to the ordinary mode of substrate **907**. Likewise, light attenuated through VOA section **903** is polarized in the ordinary mode, since core **201** is coupled to the extraordinary mode of substrate **909**. The combination of VOA section **901** and VOA section **903** thus attenuates both the ordinary and extraordinary modes.

[0060] Yet another alternative method for linearly attenuating light through a VOA is to modify the polarization mode along the VOA. For example, core **201** and cladding **203** can have cross-sectional areas that change along the length of the VOA. This change in shape with light propagation distance will modify the polarization modes along the VOA, effectively smoothing

out the polarization effects and allowing the VOA to provide attenuation independent attenuation.

[0061] The embodiments described above are illustrative of the present invention and are not intended to limit the scope of the invention to the particular embodiments described. Accordingly, while one or more embodiments of the invention have been illustrated and described, it will be appreciated that various changes can be made therein without departing from the spirit or essential characteristics thereof. For example, while the present invention describes the use of silicon to form the substrate, other materials including glass or ceramics may be used. Accordingly, the disclosures and descriptions herein are intended to be illustrative, but not limiting, of the scope of the invention, which is set forth in the following claims.